Marginal bone-level alterations of loaded zirconia and titanium dental implants: an experimental study in the dog mandible

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Abstract: OBJECTIVES The aim was to test whether or not the marginal bone-level alterations of loaded zirconia implants are similar to the bone-level alterations of a grade 4 titanium one-piece dental implant. MATERIALS AND METHODS In six dogs, all premolars and the first molars were extracted in the mandible. Four months later, three zirconia implants (BPI, VC, ZD) and a control titanium one-piece (STM) implant were randomly placed in each hemimandible and left for transmucosal healing (baseline). Six months later, CAD/CAM crowns were cemented. Sacrifice was scheduled at 6-month postloading. Digital X-rays were taken at implant placement, crowns insertion, and sacrifice. Marginal bone-level alterations were calculated, and intra- and intergroup comparisons performed adjusted by confounding factors. RESULTS Implants were successfully placed. Until crown insertion, two implants were fractured (one VC, one ZD). At sacrifice, 5 more implants were (partly) fractured (one BPI, four ZD), and one lost osseointegration (VC). No decementation of crowns occurred. All implant systems demonstrated a statistically significant (except VC) loss of marginal bone between baseline and crown insertion ranging from 0.29 mm (VC; $P = 0.116$) to 0.80 mm (ZD; $P = 0.013$). The estimated marginal bone loss between baseline and 6 months of loading ranged between 0.19 mm (BPI) and 1.11 mm (VC), being statistically significant for STM and VC only ($P < 0.05$). The changes in marginal bone levels were statistically significantly different between zirconia implants and control implants (STM vs. BPI $P = 0.007$; vs. VC $P = 0.001$; vs. ZD $P = 0.011$). CONCLUSIONS Zirconia implants were more prone to fracture prior to and after loading with implant-supported crowns compared to titanium implants. Individual differences and variability in the extent of the bone-level changes during the 12-month study period were found between the different implant types and materials.

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Marginal bone level alterations of loaded zirconia and titanium dental implants. An experimental study in the dog mandible.

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Abstract

Objectives: The aim was to test whether or not the marginal bone level alterations of loaded zirconia implants are similar to the bone level alterations of a grade 4 titanium one-piece dental implant.

Materials and methods: In 6 dogs, all premolars and the first molars were extracted in the mandible. Four months later, three zirconia implants (BPI, VC, ZD) and a control titanium one-piece (STM) implant were randomly placed in each hemi-mandible and left for transmucosal healing (baseline). Six months later, CAD/CAM crowns were cemented. Sacrifice was scheduled at 6 months post loading. Digital x-rays were taken at implant placement, crowns insertion and sacrifice. Marginal bone level alterations were calculated and intra- and intergroup comparisons performed adjusted by confounding factors.

Results: Implants were successfully placed. Until crown insertion, two implants were fractured (one VC, one ZD). At sacrifice, 5 more implants were (partly) fractured (one BPI, four ZD), and one lost osseointegration (VC). No decementation of crowns occurred. All implant systems demonstrated a statistically significant (except VC) loss of marginal bone between baseline and crown insertion ranging from 0.29mm (VC; $p=0.116$)) to 0.80mm (ZD; $p=0.013$). The estimated marginal bone loss between baseline and 6 months of loading ranged between 0.19mm (BPI) and 1.11mm (VC), being statistically significant for STM and VC only ($p<0.05$). The changes in marginal bone levels were statistically significantly different between zirconia implants and control implants (STM vs. BPI $p=0.007$; vs. VC $p=0.001$; vs. ZD $p=0.011$).

Conclusions: Zirconia implants were more prone to fracture prior to and after loading with implant-supported crowns compared to titanium implants. Individual differences and variability in the extent of the bone level changes during the 12-month study period were found between the different implant types and materials.

Introduction

Dental implants have become a predictable treatment modality for the replacement of single or multiple missing teeth (Pjetursson, *et al.* 2012). Titanium and titanium alloys are considered as gold standard and the materials of choice due to favorable physico-chemical properties and their biological attributes (osseointegration) (Brånemark, *et al.* 1977, Schroeder, *et al.* 1976). Numerous preclinical and clinical studies have documented successful hard and soft tissue integration of titanium and titanium alloy implants with predictably high survival rates over 10 years (Abrahamsson & Cardaropoli 2007, Albrektsson & Wennerberg 2004, Attard & Zarb 2004, Buser, *et al.* 2002, Buser, *et al.* 1997, Rasmusson, *et al.* 2005).

Some limitations apply, since it has been shown that during clinical function soft tissue shrinkage, recessions, and peri-implant lesions can leave the implant head visible (Cardaropoli, *et al.* 2006, Grunder 2000). In such cases and in situations with an inadequate width and/or thickness of the peri-implant mucosa, the grayish color of titanium may offer clinical disadvantages when it comes to esthetics (Jung, *et al.* 2008a, Jung, *et al.* 2007). Furthermore, there is an increasing demand for metal-free restorations from the patient's side.

To overcome these issues with metal alloys and to meet current demands, ceramic materials have been introduced in dentistry for different purposes. Basically, ceramics are available as glass ceramics or oxide ceramics. Glass ceramics are predominantly used for crowns, inlays and as veneering materials for metal-based crowns and bridges (Forberger & Gohring 2008, Manicone, *et al.* 2007). Glass ceramics are highly esthetic, but relatively weak and are not recommended for large-span bridges, posts or dental implants (Mansour, *et al.* 2008, Marquardt & Strub 2006). The development of high strength oxide ceramics has consequently become a priority, since the clinical demands for all-ceramic reconstructions and dental implants are increasing. Zirconia has been introduced in dentistry in the 1990s for frameworks of crowns and bridges, for implant abutments and more recently for dental implants (Glauser, *et al.* 2004, Kohal & Klaus 2004, Sailer, *et al.* 2007). Numerous studies demonstrated that zirconia oxide ceramics are highly biocompatible, are less prone to plaque accumulation and offer esthetic advantages over metal substrates (Jung, *et al.* 2008a, Jung, *et al.* 2007, Sailer, *et al.* 2007, Scarano, *et al.* 2004).

In vitro investigations reported improved osteoblastic cell proliferation during early stages compared to titanium (Depprich, *et al.* 2008a, Hisbergues, *et al.* 2009). Various preclinical and clinical trials demonstrated zirconia dental implants to fulfill the basic principles for successful osseointegration (Depprich, *et al.* 2008a, Depprich, *et al.* 2008b, Gahlert, *et al.* 2007, Kohal, *et al.* 2004, Oliva, *et al.* 2007). Beside well-proven mechanical properties, the biologic behavior appears to be superior to metals since ceramics do not suffer from corrosion and/or galvanic coupling. Accordingly, favorable biocompatibility with respect to soft tissue and hard tissues has been reported using zirconia ceramic materials (Ichikawa, *et al.* 1992, Piconi & Maccauro 1999).

Nevertheless, only limited information is available in the literature with respect to marginal bone level alterations of loaded zirconia dental implants in comparison to titanium dental implants (Kohal, *et al.* 2004).

The aim of the present experiment was to test whether or not the marginal bone level alterations of loaded zirconia implants are similar to the bone level alterations of a grade 4 titanium one-piece dental implant.

The hypothesis of the study was that marginal bone level alterations of loaded zirconia implants would be similar to those of a grade 4 titanium one-piece dental implant.

Materials and methods

Animals

This study was designed as a randomized experimental study employing 6 female beagle dogs. At the beginning, the animals had a mean age of 30 months (range 23 to 42) and a mean weight of 18,70 kg (range 16.6 to 22.4 kg). The study was performed at the Facultad de Veterinaria, Campus Universitario s/n, Lugo, Spain, according to the guidelines of the Spanish law of animal keeping. Prior to the beginning of the study, the experimental protocol had been approved by the local ethical committee and was subsequently performed according to the ARRIVE guidelines (Kilkenny, *et al.* 2011). The animals were kept in individual cages and had free access to chow and tap water.

Implants

Three different types of zirconia implants (test groups) and one type of titanium implant (control group) were used in the study. Two zirconia implants (VC, VITAclinical ceramic.implant, diameter 4mm, length 8mm, VITA Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany and ZD, Ziraldent, diameter 3.7mm, length 9mm, microporous surface, Metoxit AG, Thayngen, Switzerland) were one-piece implants, one zirconia implant was a two-piece implant (BPI, bpisys.ceramic, diameter 4.1mm, length 8mm, nanostructured, hydrophilic surface, BPI Biologisch Physikalische Implantate GmbH & Co., Stuttgart, Germany), while a titanium grade 4 one-piece implant (STM, Straumann Standard Tissue Level implant, diameter 3.3mm, length 8mm, made of titanium grade 4 with a sandblasted, acid-etched (SLA) surface, Institut Straumann AG, Basel, Switzerland) served as control group.

Crowns

In order to fabricate the crowns, one implant of each system was inserted in a plaster model. A standardized abutment was inserted for the STM and BPI implants, while no further abutment was connected to the VC and the ZD implant. A CAD/CAM system (Cares Visual 6.2, Straumann AG, Basel, Switzerland) was used to produce 48 identical crowns. By means of the corresponding software one abutment per group was scanned and a premolar crown was designed exhibiting the same outer shape in all four groups. In a milling machine (Straumann

Production Markkleeberg, Leipzig, Germany), 48 identical cobalt-chromium alloy crowns were milled from cobalt-chromium blanks. All crowns were then polished to a high-shine finish according to clinical standards.

Surgical procedures

All surgical procedures were performed under general and local anesthesia in an operating room. On the day of surgery the dogs were premedicated with medetomidine (0.005 mg/kg, intramusculary) and morphine (0.5 mg/kg intramusculary). Subsequently, general anesthesia was induced by injection of propofol (2mg/kg intravenously). Isofluorane (1.5-2%) and O2 (100%) were used as inhalation anesthetics. The animals were monitored routinely and further analgesia was given if necessary within the first days following all surgical procedures.

Extractions

After disinfection of the surgical site with 0.2% chlorhexidine solution (Corsodyl, GlaxoSmithKline, Brentford, Middlesex, UK), local anesthetics (Lidocaine HCl 2% with epinephrine 1:100,000; Henry Schein Inc., Port Washington, NY, USA) were administred by infiltration at the respective buccal and lingual sites. All premolars (P1, P2, P3, and P4) and the first molars (M1) were bilaterally extracted in the lower jaw and primary wound closure was obtained using resorbable sutures (Vicryl 4-0 FS2, Johnson & Johnson Medical Products, Spreitenbach, Switzerland).

Four months later, implant placement surgery was performed on both sides of the mandible in all dogs.

Implant placement

Following a mid-crestal incision from the M2 to the canine, a full-thickness mucoperiosteal flap was elevated to the buccal and lingual alveolar plate, approximately 1 to 2 mm below the mucogingival junction. All granulation tissue was carefully removed. The edentulous osseous ridge was flattened in order to obtain a width of approximately 10 mm. Eight implants were placed in each dog (4 on each side) according to the manufacturer’s recommendations. The implants were placed in a randomized manner using a computer-generated randomization list (Fig. 1A). The 4 implant types were alternated in the first dog. In all subsequent dogs, the position of the implants was altered in a clock-wise direction. The following specific protocol for each implant system was applied:

- STM implants were placed with the transition between the rough and smooth surface at the border of the bone crest. In addition, a healing abutment (1.5mm in height) was connected to the implants.
- BPI implants were installed with the transition between the threaded part of the implant and apical border of the implant shoulder at the bone crest. In addition, implants were connected with healing abutments (1.4mm in height at the distal/mesial aspect).
- VC and ZD implants were inserted with the transition between the threaded part of the implant and the apical border of the implant shoulder at the bone crest. No further abutments or healing caps were connected to VC and ZD implants. Figure 3A illustrates the position of all implants at implant placement.

This resulted in all implants being left for transmucosal healing. Following extensive rinsing with sterile saline, mucoperiosteal flaps were adapted around the implants/abutments using resorbable sutures (Vicryl 4-0 FS2, Johnson & Johnson Medical Products, Spreitenbach, Switzerland) (Fig. 1B). Subsequently, premolars and molars in the maxilla were reduced in height to avoid exessive contacts with the implants in the lower jaw during function. A postoperative regimen with antibiotics (Streptocillin, Boehringer Ingelheim Vetmedica, St. Joseph, MO, USA) was applied for 7 days to avoid infection. Further analgesia was given if necessary.

Crown insertion

Six months following implants placement, healing abutments in STM and BPI implants were removed (Fig. 1C). Standardized titanium abutments were connected to STM and BPI implants. No additional abutments were connected to VC and ZD implants (Fig. 1D). The prefabricated crowns were inserted using glass-ionomer cement (Ketac Cem, 3M Espe). Any cement excess was carefully removed and the tissues were thoroughly rinsed with sterile saline. Again, the heigth of the premolars and molars in the maxilla was evaluated and reduced to avoid excessive contact with the implants/crowns during function (Fig. 1E).

Sacrifice

After a loading period of six months following crown insertion, the animals were painlessly sacrificed by lethal doses of injected sodium pentobarbital. Implants and surrounding soft tissues were macroscopically inspected. Any local inflammation, necrosis, hemorrhage, dehiscence or any other lesion was recorded. Following dissection, the 2 hemi-mandibles were block resected and fixed by immersion in 10% formaldehyde in phosphate buffer at pH 7.

X-rays

Digital x-rays were taken using a standardized parallel technique at the day of implant placement (Fig. 2A), at crown insertion (Fig. 2B) and at sacrifice (Fig. 2C). The digitally obtained x-rays were transferred into a software program (Image J, NIH, Bethesda, USA) and the first bone-to-implant contact (fBIC) was measured on all implants for mesial and distal planes separately. For calibration purposes, the known pitch distance between the implant threads was used. The bone loss/gain was calculated as the difference of the fBIC at the day of implant placement minus the fBIC at crown insertion and sacrifice respectively. In order to account for variable reference points at the different time-points, obtained fBIC values were corrected at each time-point and for each implant system separately by the respective height of the healing abutment/abutment. Due to different reference points used in every system, the fBIC values had to be adjusted individually for each implant system by correction values (e.g. STM shoulder height of 2.8mm) (Fig. 3A).

Statistical analysis

Descriptive statistics included mean and standard deviation for the marginal bone levels, as well as median and interquartile range (IQR). These numbers are given for the three different time points, as well as for the four different implant types separately. Multiple linear mixed effects regression models were fitted to the dependent variable marginal bone levels over time (implant placement, crown insertion and 6 months post loading), for each implant type separately. In these four models, we included random effects for dog over time and adjusted for the potentially confounding factors side (right or left) and position of implant. With this approach we were able to estimate the overall and adjusted effect of time on the marginal bone levels, and using the information of every single implant in each dog. Finally, we addressed the change in marginal bone level from baseline to 6 months post loading, with a multiple linear mixed effects regression model including all implant types. Reference was the STM type, and the effects of the three zirconia implants compared to the reference titanium implant over time was estimated. All analyses were performed with R for windows and library lme4. The level of significance was set at $p<0.05$.Results

All dogs were healthy during the entire study period and neither systemic nor local adverse events were observed.

All implants could be placed according to the manufacturer's recommendations. At the day of crown insertion, two implants were fractured (one VC, one ZD). On all other implants, crowns were inserted and the implants were stable and osseointegrated. At 6 months of loading, 4 more implants were fractured below the implant neck portion (three ZD, one BPI) (Fig. 2D), one implant was partly fractured (one ZD) (Fig. 2D), while one implant had lost osseointegration (one VC) (Fig 2D). Since in one dog, 4 out of 8 implants were fractured and one implant had lost osseointegration (Fig. 2D), these data were not included in the statistical analysis. Details on fractured implants and time-points are displayed in Table 1. No decementation of crowns was noted. However, occlusal wear was observed on all crowns in all dogs.

Marginal bone levels at baseline, crown insertion and 6 months post loading (sacrifice)

Descriptive statistics are depicted in Table 2. At the day of implant insertion, the mean relative distance between the ideal insertion depth (according to the manufacturer's recommendation and corrected by the height of the transmucosal implant parts) ranged between -0.11mm (standard deviation ±0.12mm) for STM, -0.86mm (±0.29mm) for BPI, 0.31mm (±0.33mm) for VC and 0.30mm (±0.36mm) for ZD. At crown insertion and at sacrifice the respective values were 0.55mm (±0.52mm) and 0.40mm (±0.47mm) for STM, -0.25mm (±0.44mm) and -0.67mm (±0.36mm) for BPI, 0.60mm (±0.52mm) and 1.42mm (±0.5mm) for VC, and, 1.16mm (±0.81mm) and 1.13mm (±1.07mm) for ZD (Fig. 3B).

Marginal bone levels changes over time

All implant systems demonstrated a loss of marginal bone between baseline and crown insertion. For STM, the bone loss was 0.65mm ($p=0.003$), for BPI 0.61mm ($p=0.002$) and for ZD 0.80mm ($p=0.013$). For these three implant types the relative distance to the ideal marginal bone level at crown insertion was significantly larger than at baseline, while VC implants with an estimated bone loss of 0.29mm showed no significant change ($p=0.116$). These marginal bone loss values were adjusted for individual dog, side and implant position (Table 3).

The estimated marginal bone level changes from baseline to 6 months post loading (sacrifice) amounted to 0.5mm for STM ($p=0.002$), 0.19mm for BPI ($p=0.090$), 1.11mm for VC ($p<0.001$) and 0.56mm for ZD ($p=0.115$). The bone loss over time was statistically significant for STM and VC implants only. The results of the four regression analyses are displayed in Table 3.

In addition, the change in marginal bone levels over all four implant types from baseline to 6 months post loading were addressed, again adjusting for individual dog, side and position of implant. All differences between the zirconia implant types and the reference type STM were found to be statistically significant (Table 4).

Discussion

The present dog study evaluated clinical and radiographic outcomes of loaded zirconia implants in comparison to one-piece titanium dental implants over a time period of 12 months. The study revealed that one-piece zirconia implants were more prone to fracture during the healing phase and after loading compared to control titanium implant. Marginal bone level alterations of zirconia and control titanium implants revealed variability depending on the design of the implants during a 6-month healing phase and a 6-month loading period.

The predictability of titanium dental implants expanded the treatment options for fixed reconstructions in the past. Some limitations associated with titanium dental implants and the increased request from patients led to the development of zirconia dental implants. Most zirconia implants are designed as one-piece dental implants with different collar designs emerging through the mucosa. From a prosthetic point of view, the close relationship of the implant neck with the marginal mucosa eases the clinical procedure and avoids the need for a second stage surgery (abutment connection). Surgically, the one-piece design is associated with limitations since the coronal part of the implants is exposed to the oral cavity. The healing phase leading to a full osseointegration of the intrabony part of the implant may be disturbed by forces applied during function. In the present study, 7 zirconia implants fractured either during the healing period or during the 6-month loading period and in addition, many implant demonstrated occlusal wear at the day of crown insertion (please see Figure 2D). Only one zirconia implant presented a loss of osseointegration, thereby demonstrating that osseointegration was successful in all but one implant case and similar to the titanium control implants. This is in agreement with preclinical data obtained in earlier studies confirming that osseointegration of zirconia implants can be successfully achieved (Calvo-Guirado*, et al.* 2013, Gahlert*, et al.* 2012, Moller*, et al.* 2012, Shon*, et al.* 2013). From a clinical point of view, not only a successful osseointegration is needed, but also stability and resistance to fracture. Out of 7 fractured implants, 4 belonged to the same implant system (ZD), revealing limitations possibly related to the design concept and fracture occurring at the narrowest part of the implant. In addition, 4 out of 7 fractures occurred in the same dog, thereby adding a confounding factor of the animal. Due to these outcomes, this dog was not taken into the statistical analysis. In addition, it is of importance to mention that most fractures occurred with one-piece zirconia implants, but not with the two-piece zirconia implants. The two-piece zirconia implants (BPI) were connected to healing abutments during the initial healing phase. The height of the healing abutments was in range similar to the titanium implants, but less high than the one-piece zirconia implants. Therefore, the healing period may have been less affected by occlusal forces on this particular two-piece zirconia implant. In addition, there appears to be a minimal implant diameter needed to withstand forces during the healing phase. This is based on the fact that most except for one fracture (4.0mm), all fractured implants had a diameter of less than 4mm. All, but one fracture (partial), occurred at a level below the implant shoulder, probably resembling the weakest point of the respective systems. In addition, many of the zirconia implant heads demonstrated wear at the day of crown insertion. Similar observations with one-piece zirconia implants not withstanding the occlusal forces during the healing phase were made earlier (Koch*, et al.* 2010). In that study, the overall rate of implants demonstrating cracks of the implant head amounted to 30%. Clinically, one-piece dental implants are documented in a variety of studies ranging from immediate implants with immediate function to delayed implant placement and delayed functional loading (Blaschke & Volz 2006, Oliva*, et al.* 2008, 2010, Payer*, et al.* 2013). Clinical survival rates appear to be quite high ranging from 84% after 21 months to 98% after 1 year (Andreiotelli*, et al.* 2009). Limitations may still apply and in one retrospective study, evaluating one-piece zirconia implants, a high percentage of fractures was observed (Gahlert*, et al.* 2013). The fractures were mainly associated with small diameter implants below 4mm. This underlines the necessity to consider the manufacturer's recommendations, to make a careful choice for the correct implant diameter and the limits of certain designs of zirconia implants for specific locations and loading conditions. No decementation of crowns occurred during the entire study period in the present study. This demonstrated that, prosthetically, the implant design might work well, fulfilling the clinical needs. Similar observations were made in a preclinical experiment in monkeys. In that study, zirconia implants and titanium implants were loaded using non-precious single crowns, reporting no prosthetic complications (Kohal*, et al.* 2004).

The marginal bone level alterations of one- and two-piece dental implants in the present study revealed variability with respect to the extent and the timing of the bone loss. The predominant changes (loss) for the two-piece zirconia implant (BPI), one of the one-piece zirconia implants (ZD) and the titanium control implant (STM) occurred during the healing phase following implant placement. For the remaining one-piece zirconia implant (VC), these changes predominantly occurred after crown insertion. These differences in the changes of the marginal bone level may be attributed to individual design differences of the respective implants. Literature on titanium dental implants reports on marginal bone loss depending on the type of implant (Hermann*, et al.* 2000, Thoma*, et al.* 2013). For two-piece dental implants, the physiologic adaptation of the marginal bone is expected to take place after abutment connection in case the implants are left for submerged healing (Abrahamsson*, et al.* 1999, Ericsson*, et al.* 1996, Roos*, et al.* 1997), while for one-piece dental implants, marginal bone level alterations start at the day of implant placement (Abrahamsson*, et al.* 1996, Hermann*, et al.* 2001). Due to the fact that in the present study, all implants (even the two-piece zirconia implant) were left for transmucosal healing, differences could not be attributed to a specific implant type (one- or two-piece). The extent of the marginal bone level alterations at the end of the 6-month loading period revealed that for the two-piece zirconia implant (BPI) the marginal bone level was close to the implant-abutment junction. This outcome has been reported for two-piece titanium and titanium-zirconium implants with platform shifting in preclinical studies earlier (Jung*, et al.* 2008b, Thoma*, et al.* 2011). For the two one-piece zirconia implants (VC, ZD), the marginal bone level was located between 1.13mm (ZD) and 1.42mm (VC) below the implant shoulder. The literature reports no data on the VC implant and only preliminary data on the ZD implant (Kohal*, et al.* 2010, Sperlich*, et al.* 2012), but similar implant designs (one-piece) revealed bone levels between 1.31mm and 1.95mm below the crest at 12 to 48 months time-points in clinical studies (Borgonovo*, et al.* 2013, Kohal*, et al.* 2012, Kohal*, et al.* 2013).

Conclusions

In the present preclinical study it is concluded that the implant design of three zirconia dental implants had a strong impact in terms of fracture resistance during the healing phase (osseointegration) and during the 6-month loading period. The marginal bone level alterations varied depending on the implant design, with some implants demonstrating more marginal bone level alterations during the osseointegration phase and others showing more changes during the 6-month loading period. Care needs to be taken when choosing zirconia implants in daily clinical practice since many available implants do not have clinical data neither short nor long-term.

Acknowledgements and conflict of interest

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Legends: Tables and Figures

Table 1. List of complications noted at crown insertion and 6 months post loading

Table 2. Descriptive statistics of marginal bone levels for all implant systems at three time-points (baseline, crown insertion, 6 months post loading). n= number ; SD = standard deviation ; Q1 = first interquartile ; Q3 = third interquartile.

Table 3. Marginal bone level changes from baseline to crown insertion and from baseline to 6 months post loading. Results of four multiple linear mixed effects regression models for the dependent variable measurement. Each model contains random effects for dogs over time and fixed effects for side and implant site. The models are fitted separately to each implant type.
* CI = confidence interval.

Table 4. Marginal bone level changes from baseline to 6 months post loading including all four implant types; Result of a multiple linear mixed effects regression model for the dependent variable measurement at 6 months, adjusted for measurement at crown insertion, including all implant types, adjusting for side and implant site, with random effects for dog. * CI = confidence interval.

Figure 1. Implant insertion in a right mandible. From left to right: VC, STM, ZD, BPI. A. Occlusal view after implant placement. B. Situation after flap closure and C. at crown insertion. All implants were placed in a transmucosal way. D. Buccal view after insertion of the abutments of STM and BPI implants (day of crown insertion). E. Buccal view after insertion of crowns.

Figure 2. Standardized x-rays obtained at implant placement (A), at abutment connection/crown insertion (B) and at sacrifice (C). Implant systems from left to right: STM, ZD, BPI, VC. (D) implants with fractures and loss of osseointegration.

Figure 3. Illustrations demonstrating the ideal vertical position of all four implants system types with the respective levels relative to the bone crest. From left to right: STM, BPI, ZD, VC. A. at the time of implant placement (baseline). B. at sacrifice.

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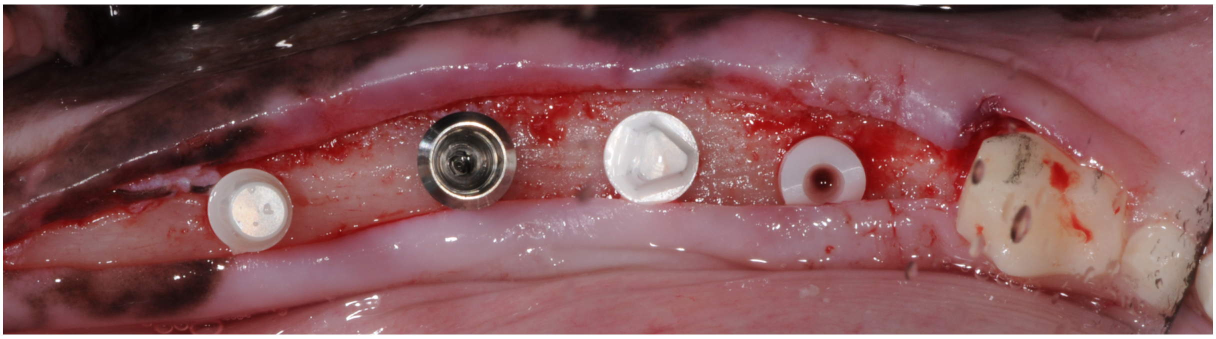
Figure 1

A



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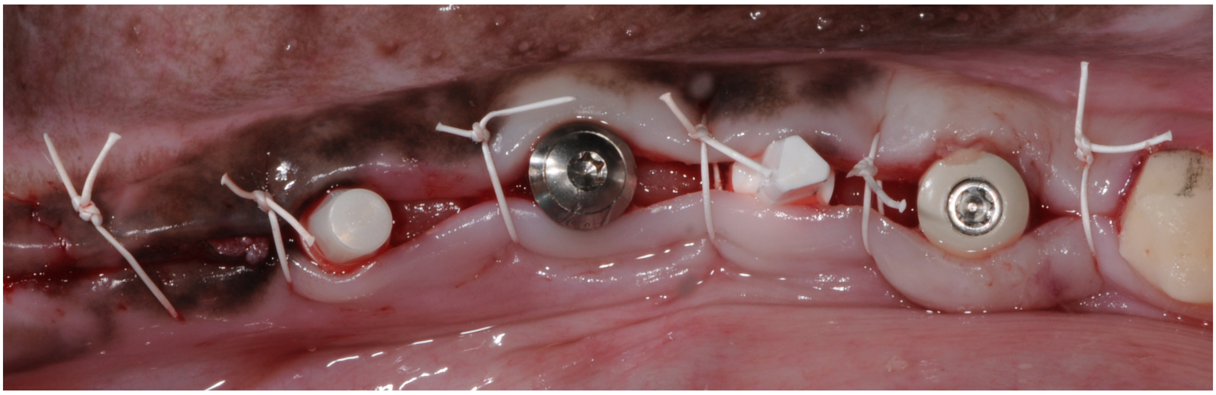

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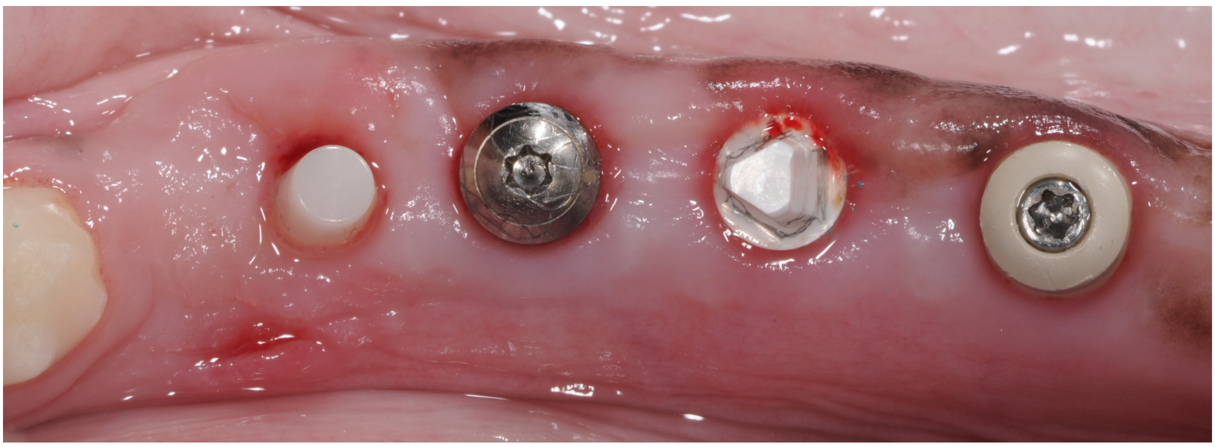

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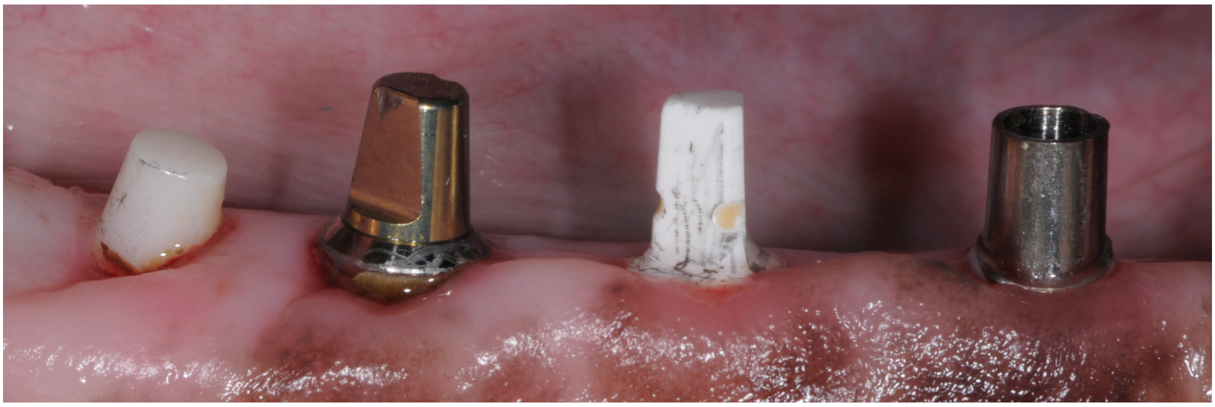

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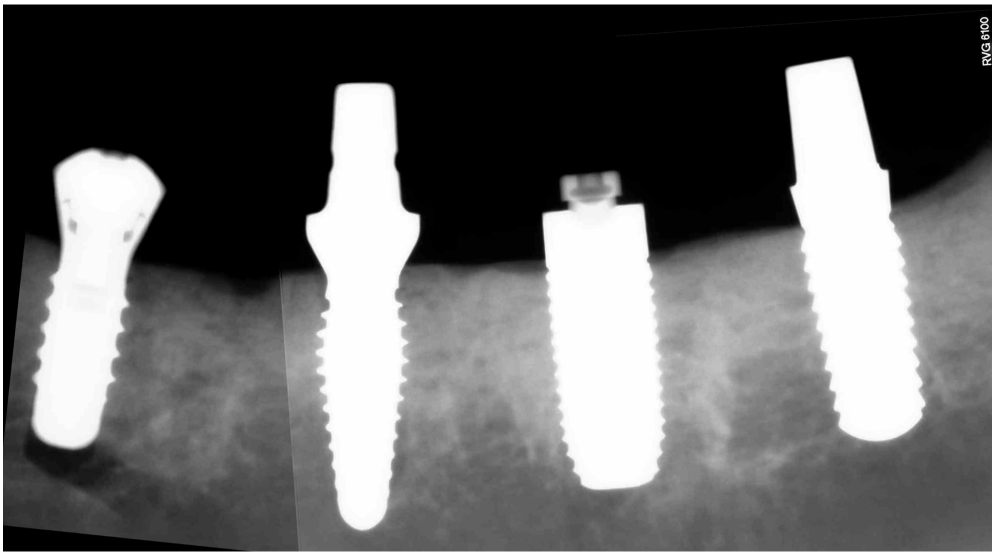
Figure 2

A



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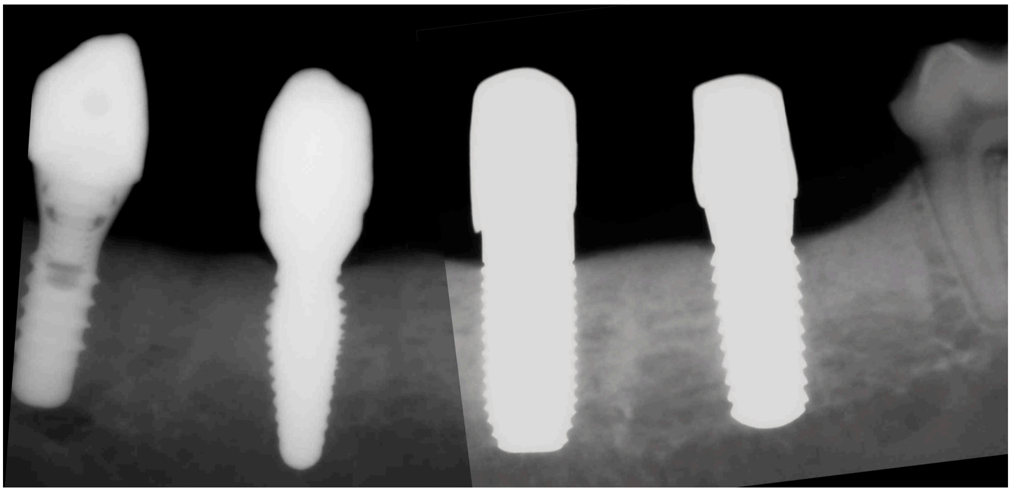

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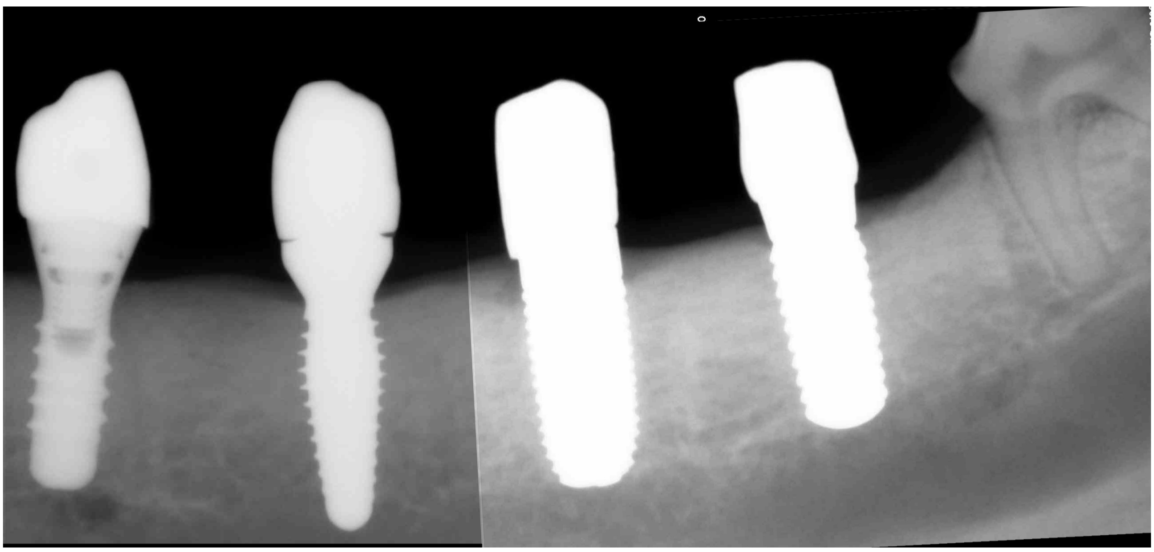

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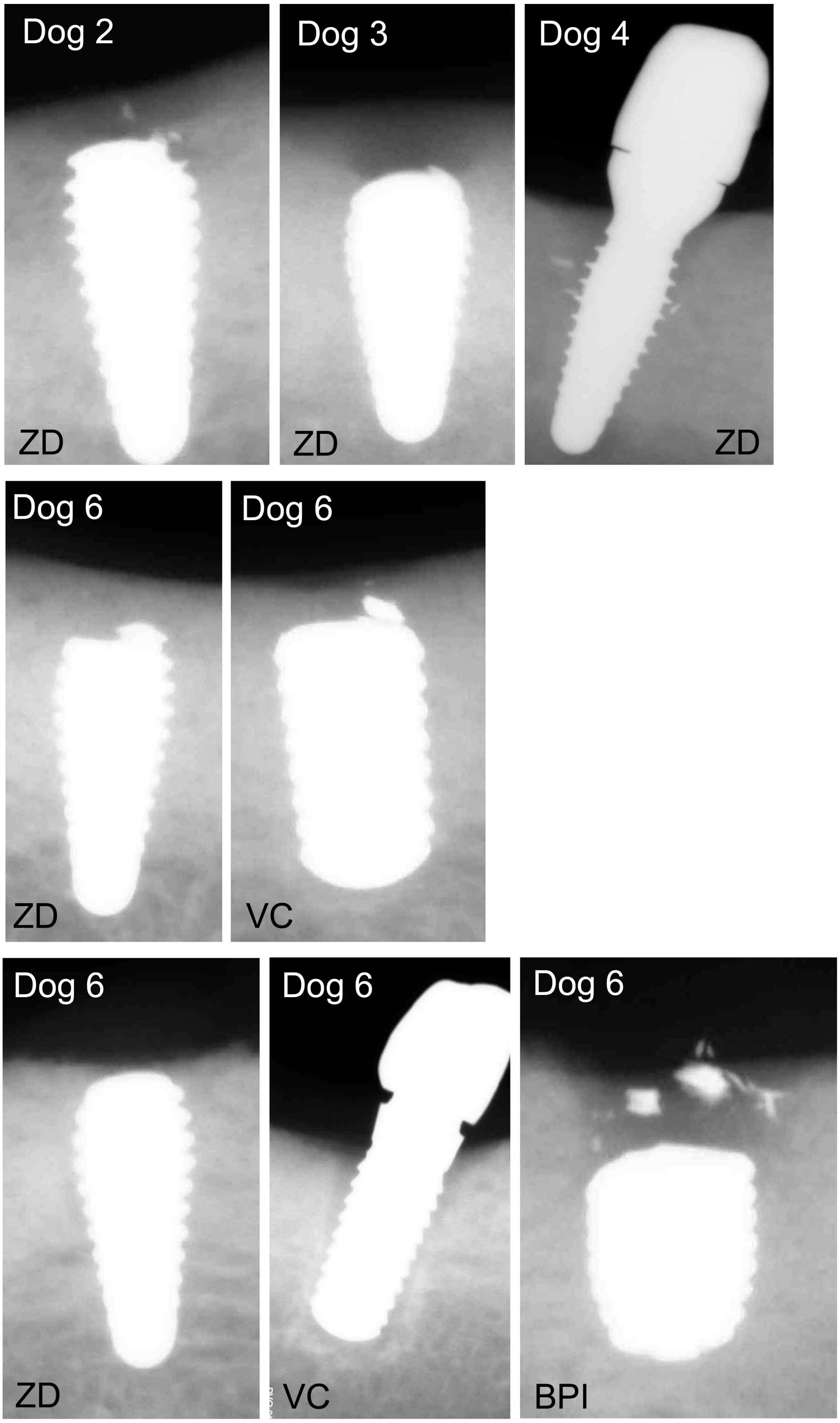
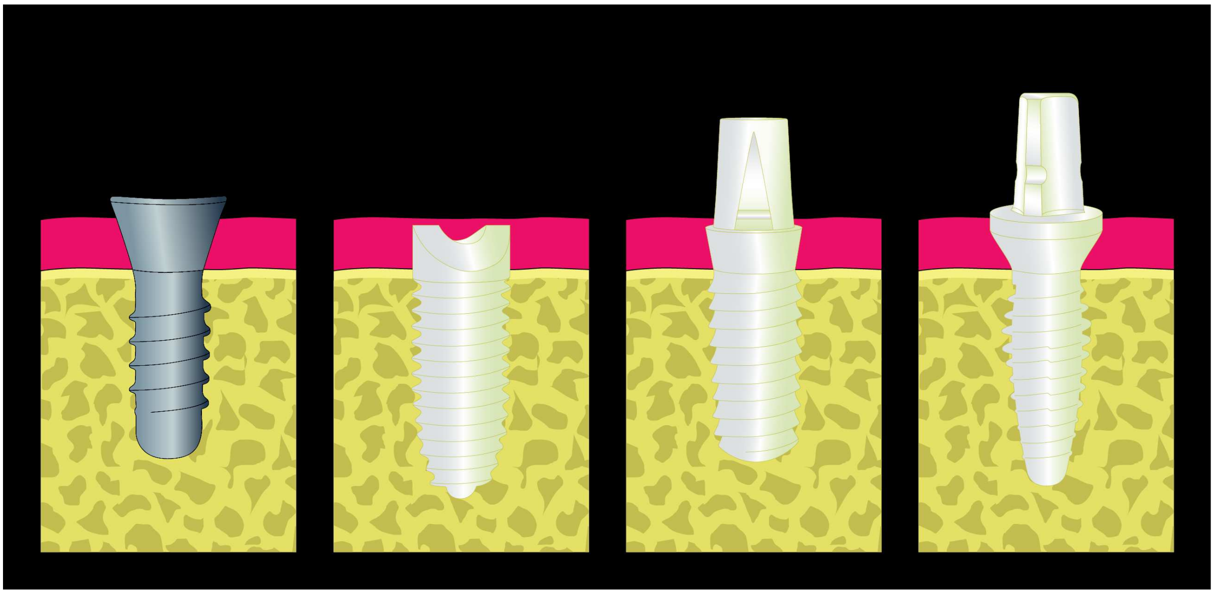


Figure 3.
A.



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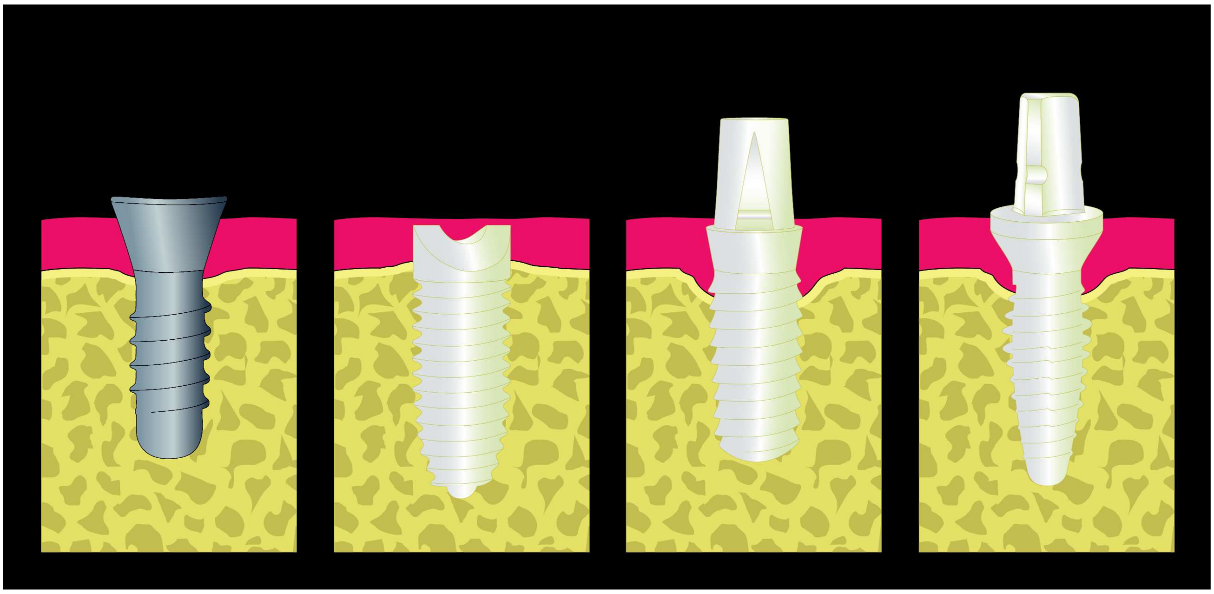

Table 1.

dog number	side	site	group	crown insertion	6 months
2	L	3	ZD	osseointegrated	fracture
3	R	1	ZD	osseointegrated	fracture
4	R	4	ZD	osseointegrated	partly fractured
6	R	1	BPI	osseointegrated	fracture
6	L	1	VC	fracture	fracture
6	R	4	VC	osseointegrated	no osseointegration
6	L	3	ZD	fracture	fracture
6	R	2	ZD	osseointegrated	fracture

Table 2

Time Point	**STM**	**BPI**	**VC**	**ZD**
	n implants n dogs n sites Mean ± SD Median (Q1, Q3)	n implants n dogs n sites Mean ± SD Median (Q1, Q3)	n implants n dogs n sites Mean ± SD Median (Q1, Q3)	n implants n dogs n sites Mean ± SD Median (Q1, Q3)
Baseline	10 5 4 -0.11 ± 0.12 -0.12 (-0.13, -0.03)	10 5 4 -0.86 ± 0.29 -0.82 (-0.94, -0.77)	10 5 4 0.31 ± 0.33 0.36 (0.27, 0.53)	10 5 4 0.30 ± 0.36 0.25 (0.02, 0.41)
Crown insertion	10 5 4 0.55 ± 0.52 0.47 (0.34, 0.77)	10 5 4 -0.25 ± 0.44 -0.14 (-0.60, 0.10)	10 5 4 0.60 ± 0.52 0.69 (0.42, 0.93)	9 5 4 1.16 ± 0.81 0.93 (0.59, 1.3)
6 months post loading	10 5 4 0.40 ± 0.47 0.48 (0.17, 0.61)	10 5 4 -0.67 ± 0.36 -0.72 (-0.94, -0.53)	10 5 4 1.42 ± 0.5 1.56 (1.31, 1.76)	6 4 4 1.13 ± 1.07 0.74 (0.60, 0.96)

Table 3.

Model	Implant type	Time point	Effect	95%-CI*	p-Value
1	STM	Crown insertion	0.65	0.18-1.12	**0.003**
		6 Months	0.50	0.15-0.85	**0.002**
2	BPI	Crown insertion	0.61	0.20-1.00	**0.002**
		6 Months	0.19	-0.08-0.46	0.090
3	VC	Crown insertion	0.29	-0.18-0.76	0.116
		6 Months	1.11	0.64-1.58	**<0.001**
4	ZD	Crown insertion	0.80	0.09-1.51	**0.013**
		6 Months	0.56	-0.36-1.48	0.115

Table 4

Type	Effect	95%-CI*	p
BPI vs. STM	-1.04	-1.86 - -0.22	0.007
VC vs. STM	1.04	0.40-1.66	0.001
ZD vs. STM	0.78	0.11-1.45	0.011